# Applied Nanotechnology for Human Space Exploration

**Leonard L. Yowell**
NASA Johnson Space Center

February 20th, 2007

*E-Mail: leonard.yowell-1@nasa.gov*
*Phone: 281-483-2811*

# NASA's Strategic Vision

Deep Space Exploration

Mars Manned

Mars Robotic

Crew Exploration Vehicle

Lunar Manned

Lunar Robotic

ISS Complete

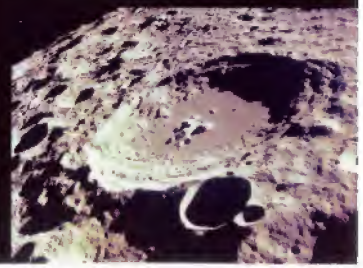
2005

2010

2015

2020

2035



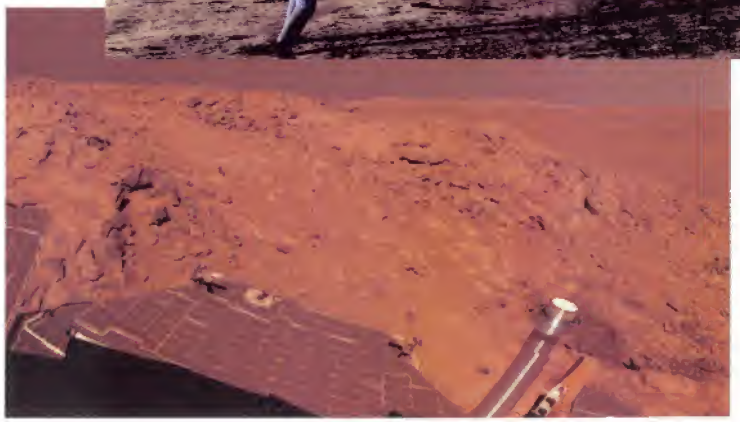
# Exploration Architecture

Launch Vehicles

Lunar / Interplanetary Transfer

Lunar Surface Operations

Crew Exploration Vehicle (CEV)
ISS Operations



Planetary Operations
(Human/Robotic)

# Future Exploration Mission Requirements Cannot Be Met with Conventional Materials

## Vehicles and Habitats

- Reduced mass and volume
- High strength
- Thermal and radiation protection
- Self-healing, self-diagnostic
- Multi-functionality
- Improved durability
- Environmental resistance (dust, atmosphere, radiation)

## EVA Suits

- Reduced mass
- Increased functionality and mobility
- Thermal and radiation protection
- Environmental resistance

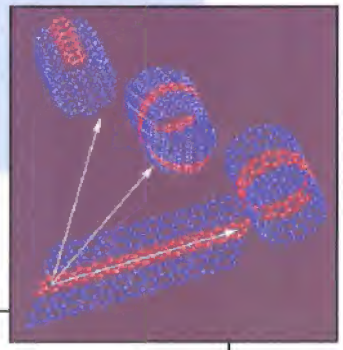
## Satellites and Rovers

- Reduced mass and volume
- Reduced power requirements
- Increased capability, multifunctionality

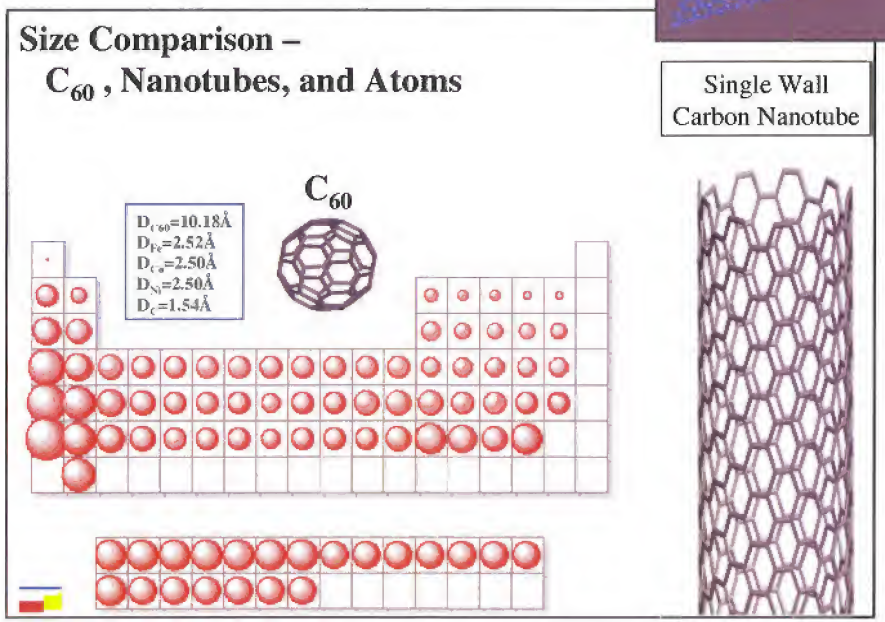
# Nanomaterials: Single Wall Carbon Nanotubes

## Unique Properties

- Exceptional strength
- Interesting electrical properties (metallic, semi-conducting, semi-metal)
- High thermal conductivity
- Large aspect ratios
- Large surface areas



Single Wall Carbon Nanotube



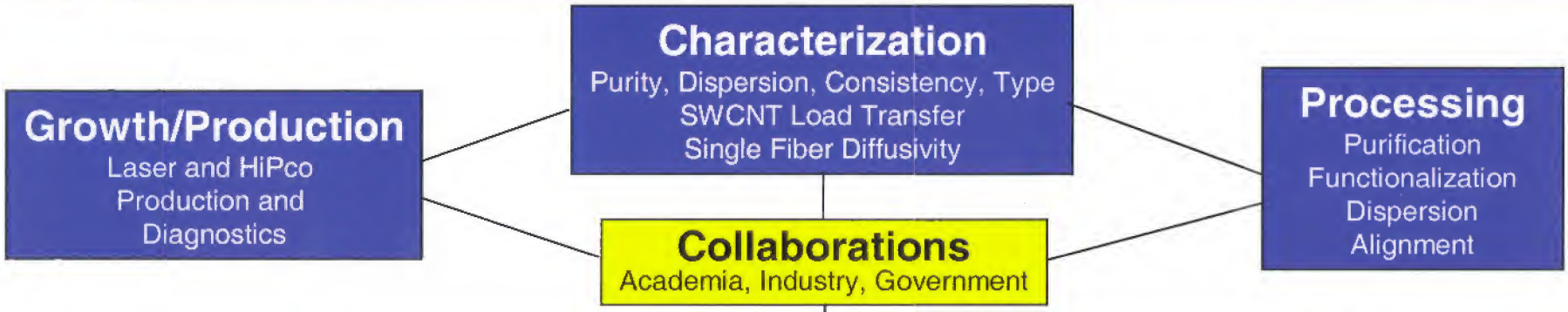

## Possible Applications

- High-strength, light-weight fibers and composites
- Nano-electronics, sensors, and field emission displays
- Radiation shielding and monitoring
- Fuel cells, energy storage, capacitors
- Biotechnology
- Advanced life support materials
- Electromagnetic shielding and electrostatic discharge materials
- Multifunctional materials
- Thermal management materials

## Current Limitations

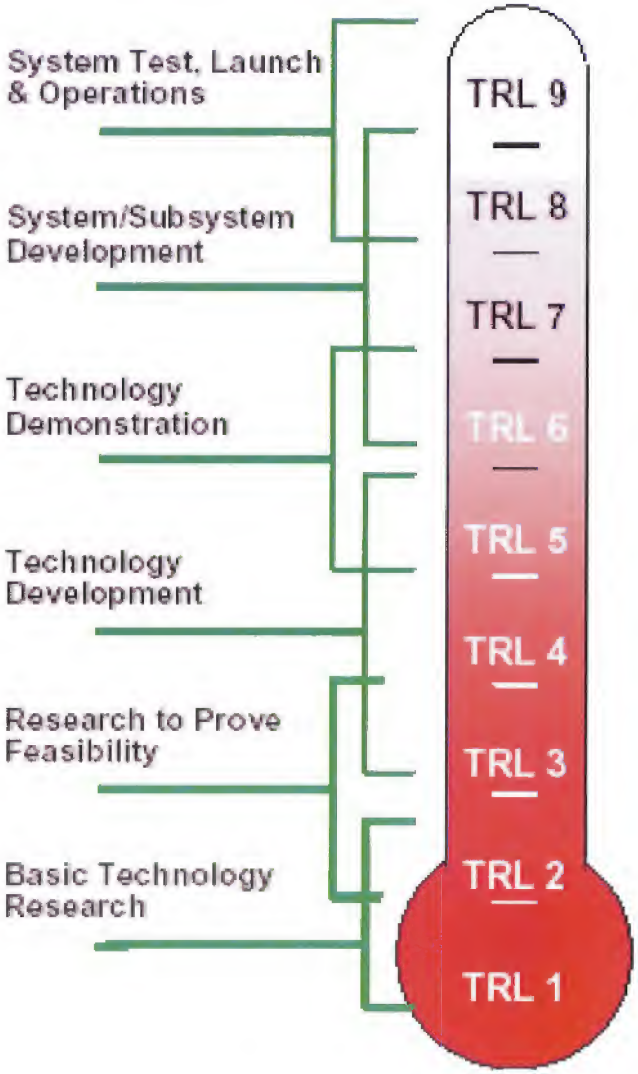
- High cost for bulk production
- Inability to produce high quality, pure, type specific SWCNTs
- Variations in material from batch to batch
- Growth mechanisms not thoroughly understood
- Characterization tools, techniques and protocols not well developed

# Applied Nanotechnology at JSC: Fundamentals to Applications




| APPLICATIONS | PARTNERS | TRL 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Supercapacitors | EP, GRC, Industry | X | X | X | X | |
| ESD / EMI Shielding | EV, OA, Rice, UTPA, UTD, Industry | X | X | X | | |
| Regenerable $CO_2$ Removal | EC, ARC, Rice, UTA Industry | X | X | | | |
| Proton Exchange Membrane – PEM - Fuel Cells | EP, GRC, Industry | X | X | | | |
| Water Disinfection & Recovery | EC, Industry | X | X | | | |
| Active / Passive Thermal Management Materials for Space | EC, Rice, Industry | X | X | | | |
| Multifunctional Materials: Thermal Radiation & Impact Protection (TRIPS) | ES3, ARC, Rice, Industry | X | X | | | |
| Nanotube-Based Structural Materials & Advanced Repair | EC, MA, ES3, Rice | X | X | | | |
| Radiation Dosimeter | NX, Rice, PV, Ames | X | | | | |

# Technology Readiness Levels (TRL)




Actual system "flight proven" through successful mission operations

Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principles observed and reported

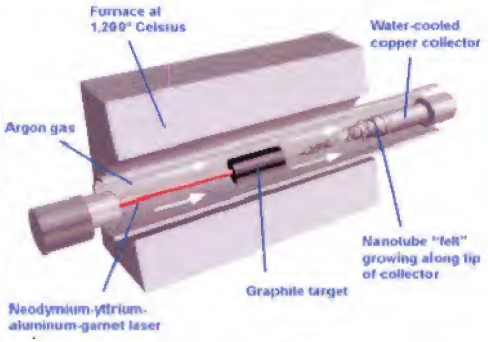
# Growth, Modeling, Diagnostics and Production

**Objective:** Ensure a reliable source of single wall carbon nanotubes with tailored properties (length, diameter, purity, chirality)

## Laser Ablation

Graphite $\xrightarrow[\text{4000-5000 K, argon}]{\text{Co, Ni Catalysts}}$ fullerenes + SWCNT + impurities

- Batch process
- ~1g/day
- Large diameters (~1.4nm)



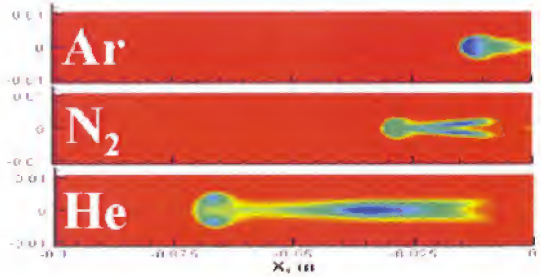

## High Pressure CO (HiPco)

CO + CO $\xrightarrow[\text{900-1200C, 10-40 atm}]{\text{Fe, Ni Catalysts}}$ $CO_2$ + SWCNT + impurities

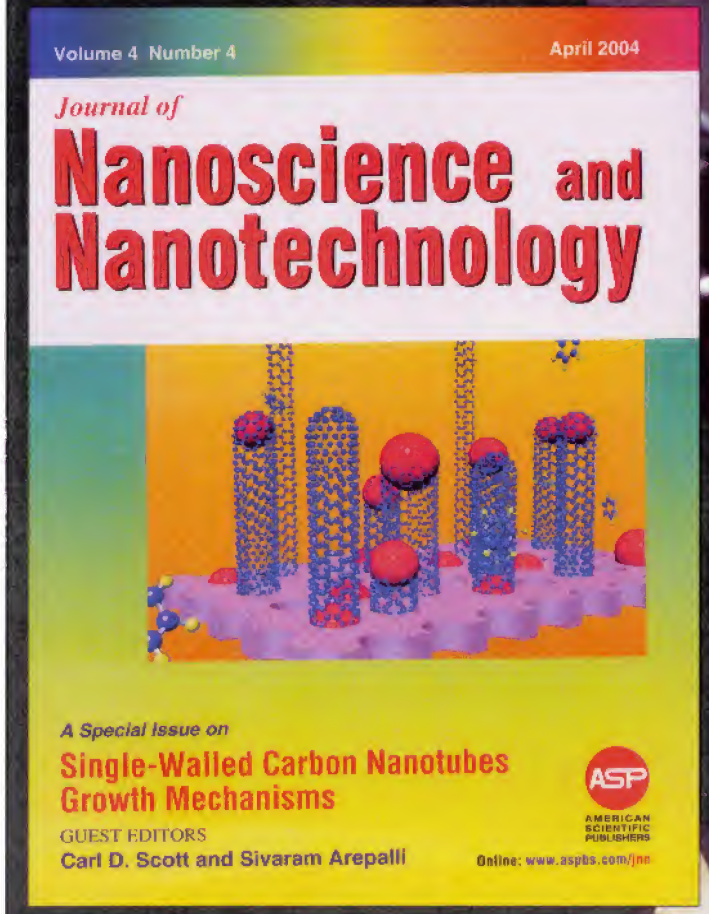
- Continuous process
- 10-100's g/day
- Small diameters (0.9nm)
- Company spin-off (CNI)

Rice Univ. & NASA → Carbon Nanotechnologies, Inc.

Modeling, Diagnostics, and Parametric Studies




# Growth, Modeling, Diagnostics and Production



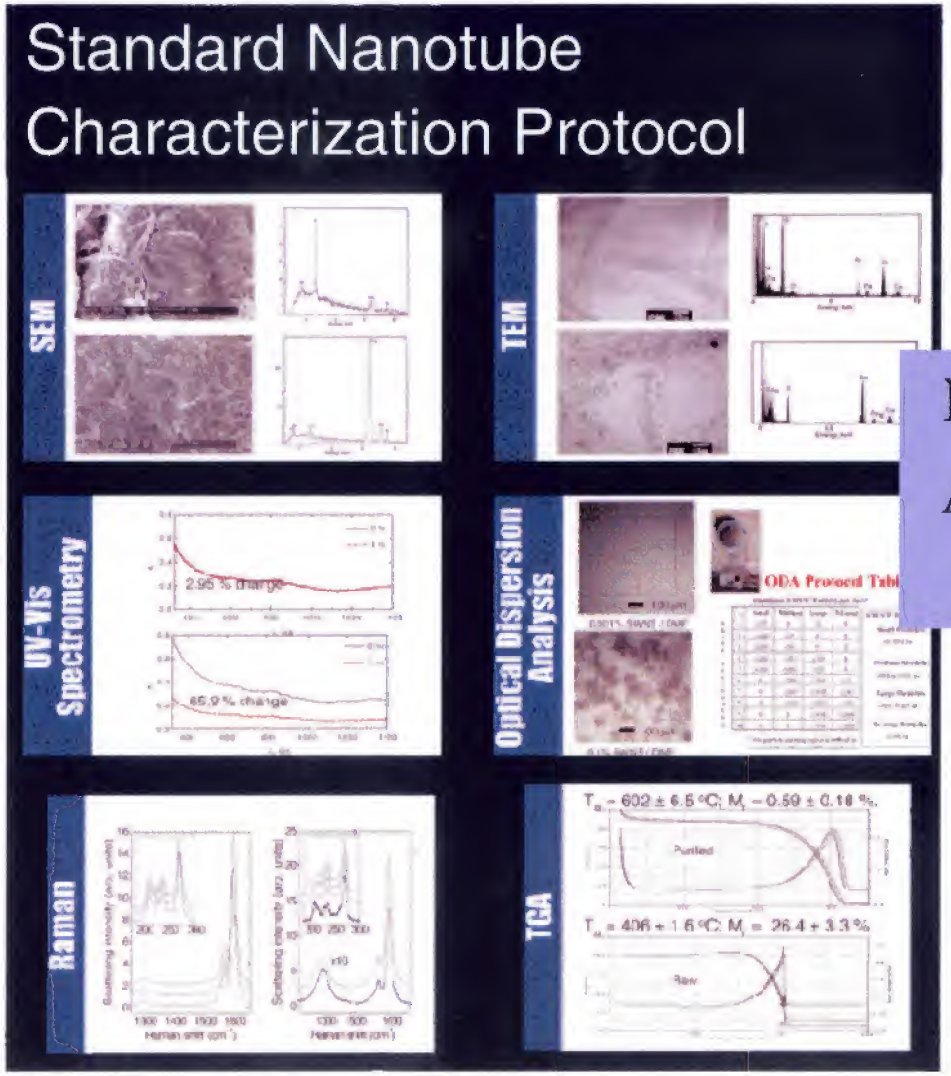

NASA / Rice University

3rd Single-Wall Nanotube Growth Mechanisms Workshop

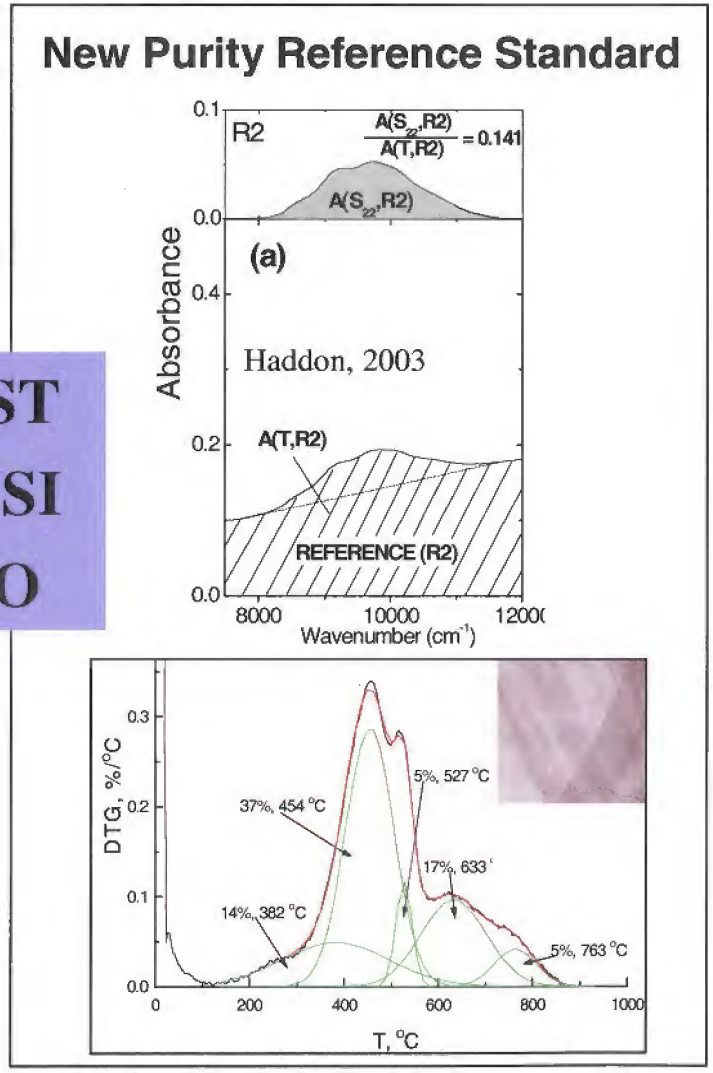
April 2007

Canyon of the Eagles Ranch, Texas

# Characterization: Purity, Dispersion & Consistency



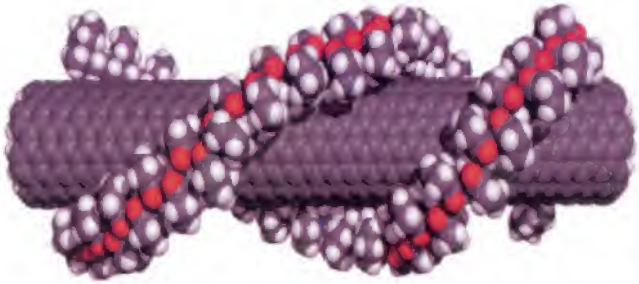

NIST
ANSI
ISO

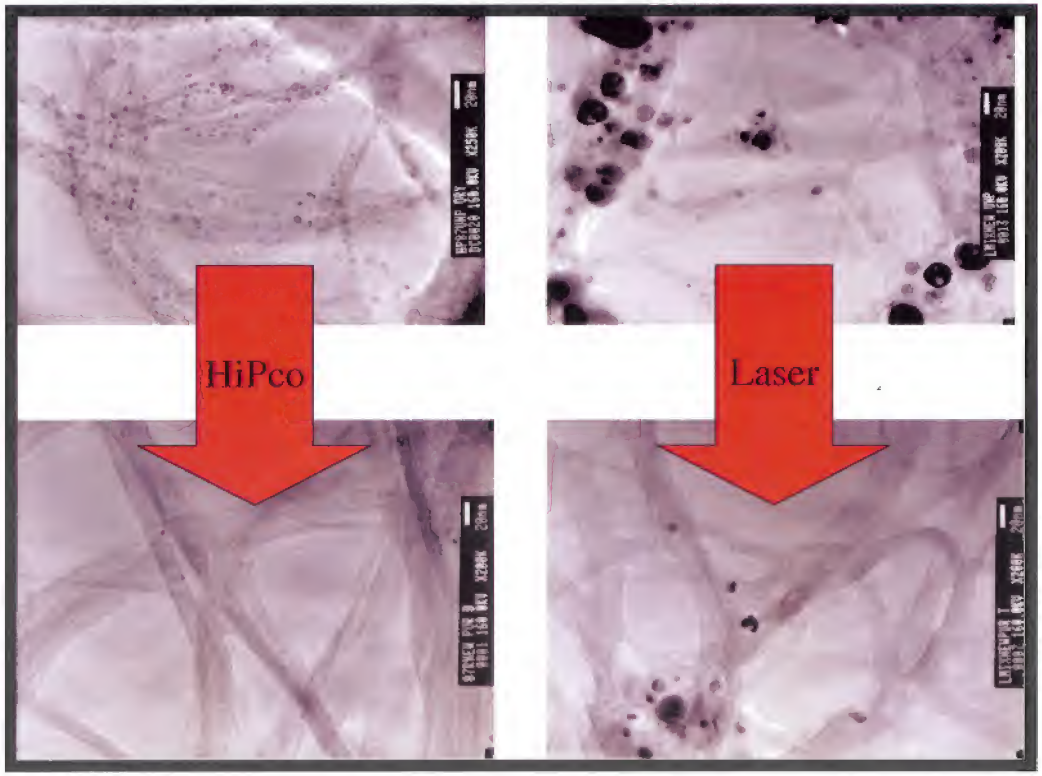


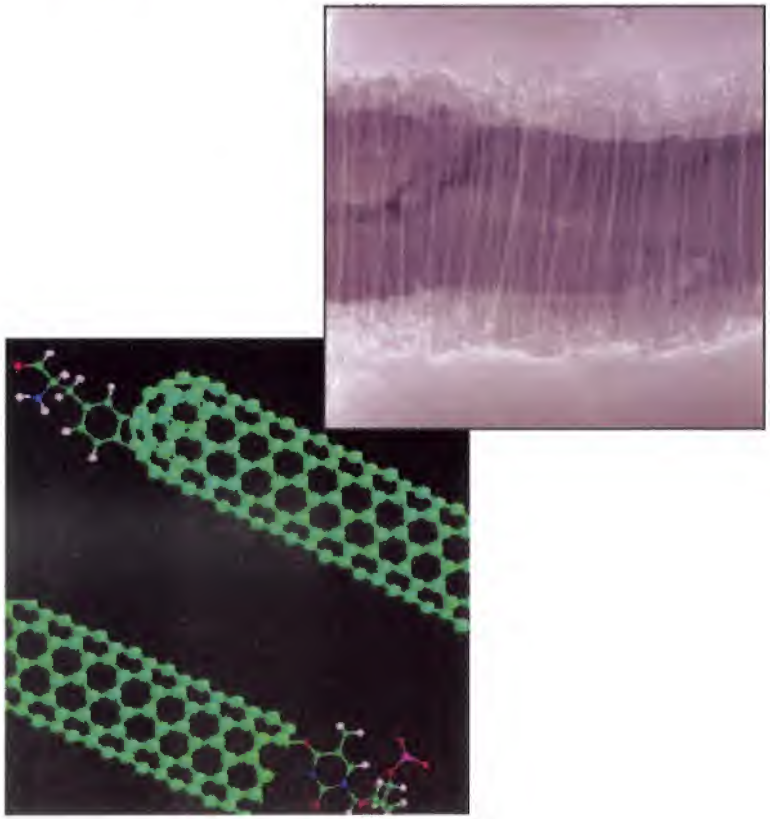

Arepalli, et al., Carbon, 2004

# Processing

* Dispersion
* Purification
* Functionalization
* Alignment
* Surface Area





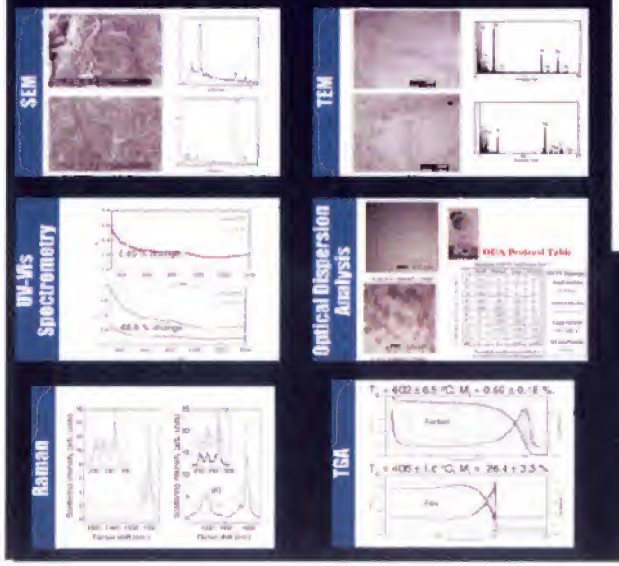
# Nanoelectronics: Enabling Technologies

## Nano-Fabrication


(10,10) Armchair Tube

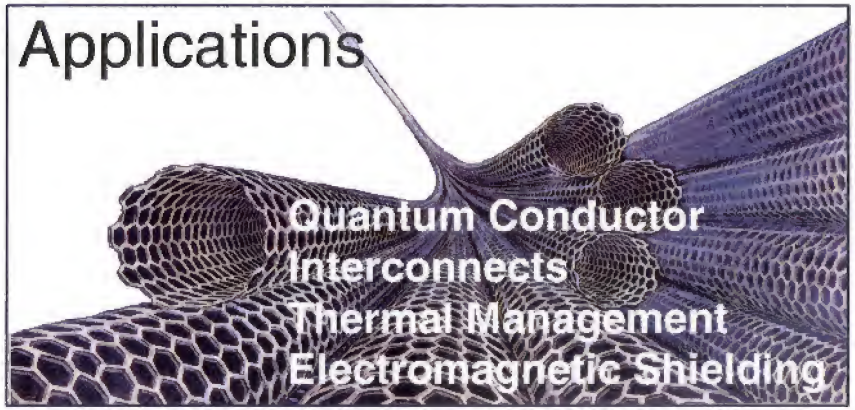
## Nano-Characterization

Standard Nanotube Characterization Protocol

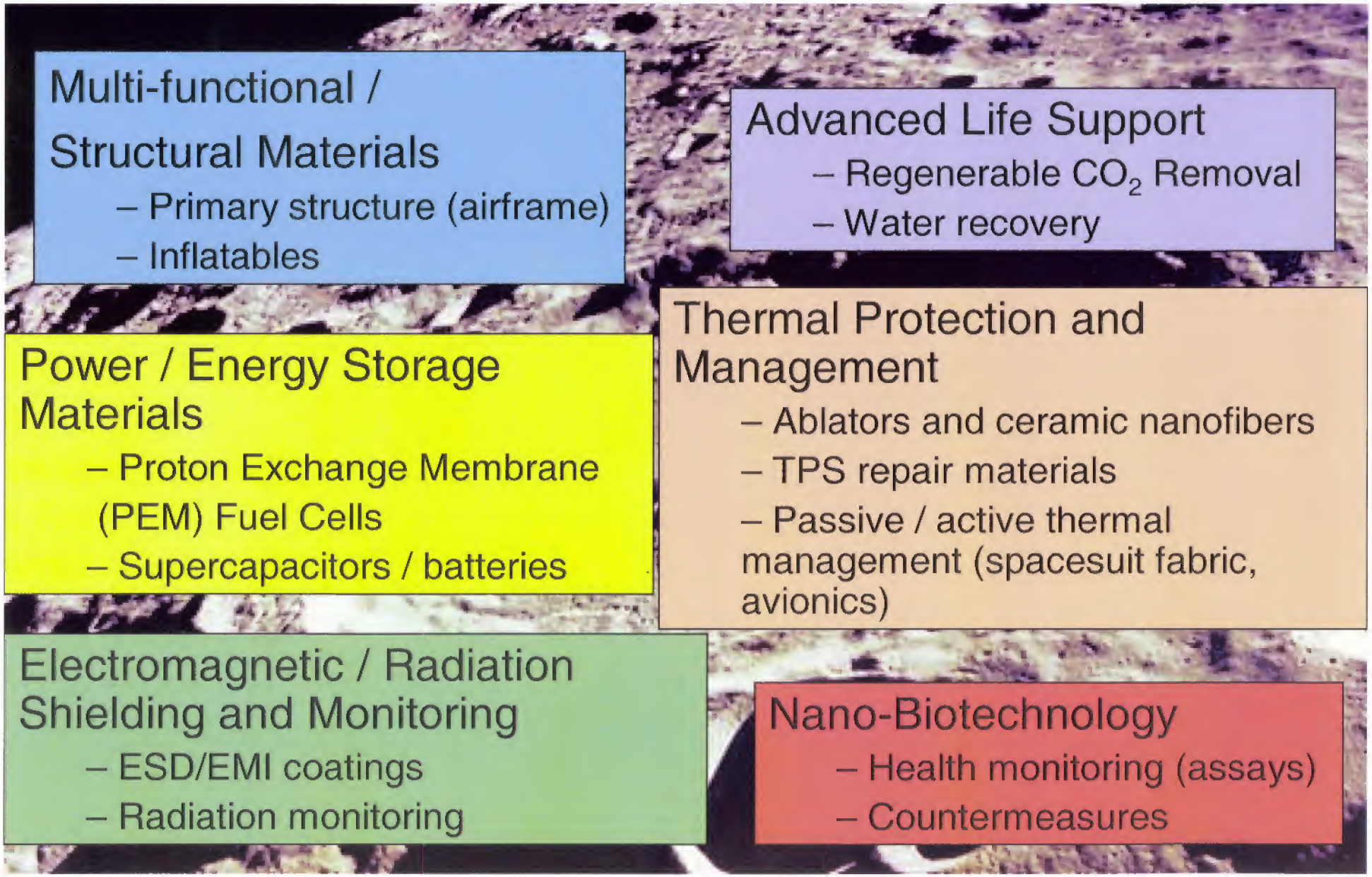



**Type-Specific Nanotube Synthesis**

## Applications




# Applications for Human Space Exploration



## Multi-functional / Structural Materials

- Primary structure (airframe)
- Inflatables

## Advanced Life Support

- Regenerable $CO_2$ Removal
- Water recovery

## Power / Energy Storage Materials

- Proton Exchange Membrane (PEM) Fuel Cells
- Supercapacitors / batteries

## Thermal Protection and Management

- Ablators and ceramic nanofibers
- TPS repair materials
- Passive / active thermal management (spacesuit fabric, avionics)

## Electromagnetic / Radiation Shielding and Monitoring

- ESD/EMI coatings
- Radiation monitoring

## Nano-Biotechnology

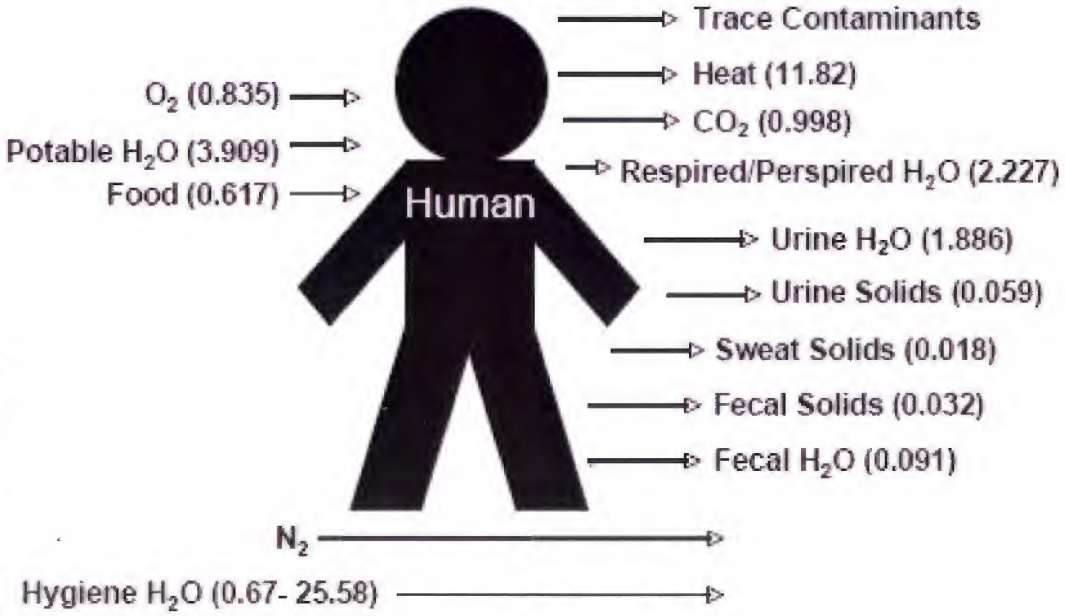
- Health monitoring (assays)
- Countermeasures

# Exploration Life Support

**CHALLENGE:**

Supply the daily needs of humans for long duration missions

- Air Revitalization
- Food Management
- Solid Waste Management
- Thermal Control
- Water Reclamation




Human consumable and throughput values in kg/crewmember/day Klaus et al, 2005

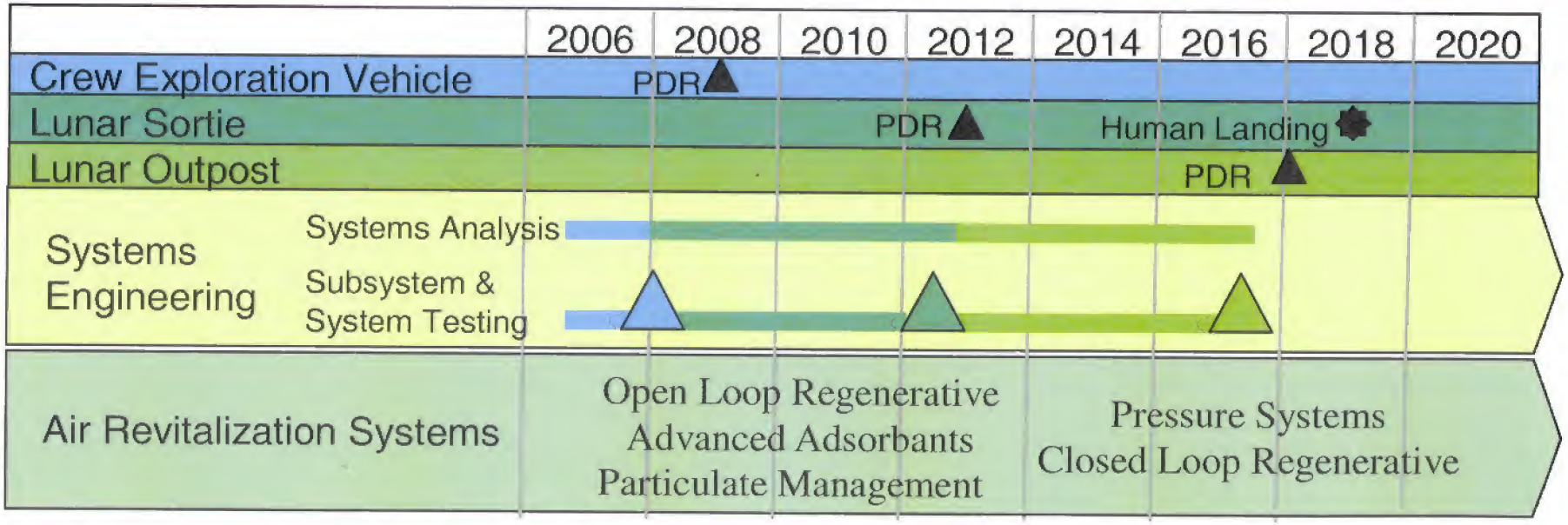
# Exploration Life Support: Atmosphere Revitalization System

**MISSION:**

- Vehicle cabin atmospheric pressure & quality
- Atmospheric gas storage, supply and distribution
- Carbon dioxide partial pressure control
- Trace contaminant & particulate control
- Resource recovery, storage and distribution
- Lower spacecraft complexity = Lower risk
- Lower risk = Greater safety

LiOH Canisters

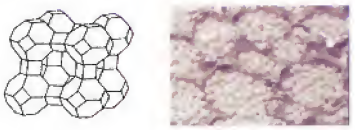
Experimental Regenerable System



# Advanced Life Support: Regenerable $CO_2$ Removal

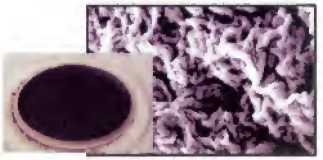
## CHALLENGE:

- Long duration space flight requires a regenerable system for air revitalization
- NASA need: lower mass, higher performance, reduced volume



**Current RCRS materials: Zeolites and amine-coated polymer beads.**

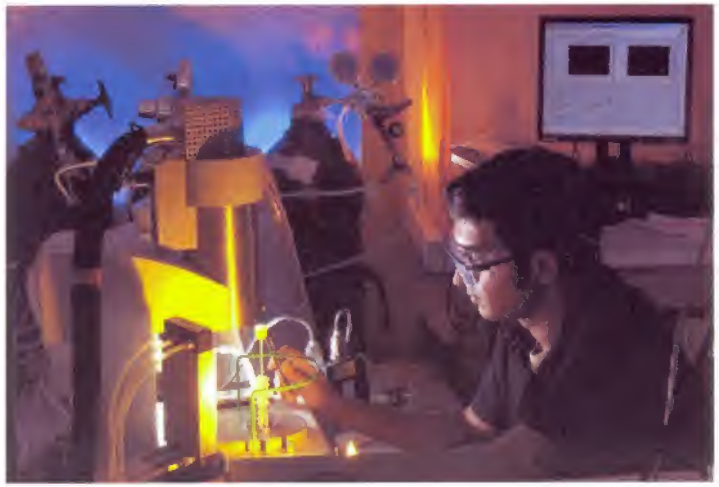
**To be replaced by**



**Single Wall Carbon Nanotube (SWCNT) Structure**

## SOLUTION:

- Carbon Nanotubes: superior surface area & thermal conductivity
- Functionalized with $CO_2$ scrubbing chemistry – less volatile
- Suitable for both EVA and vehicle applications
- Applicability to smokestack applications on Earth



Micro-scale testing with thermo-gravimetric analysis

## COLLABORATION:

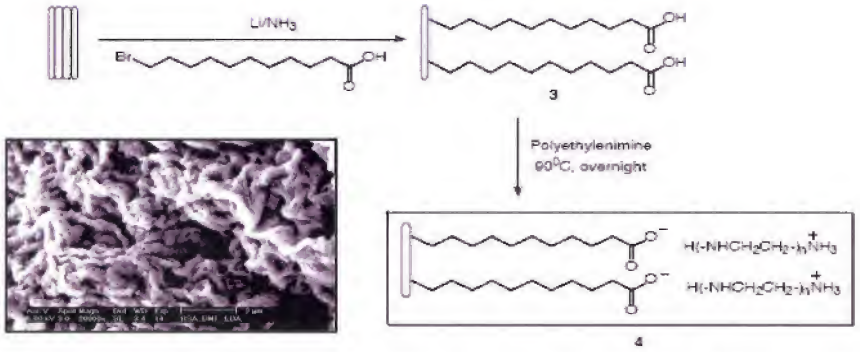
- Rice University: Nanotube functionalization
- UTA: Primary amine chemistry
- JSC (EC): Requirements for space systems
- NASA Ames: Nanomaterials for trace contaminant control system & $CO_2$ Sensors
- Energy industry participation interest

RICE UTA University of Hartford

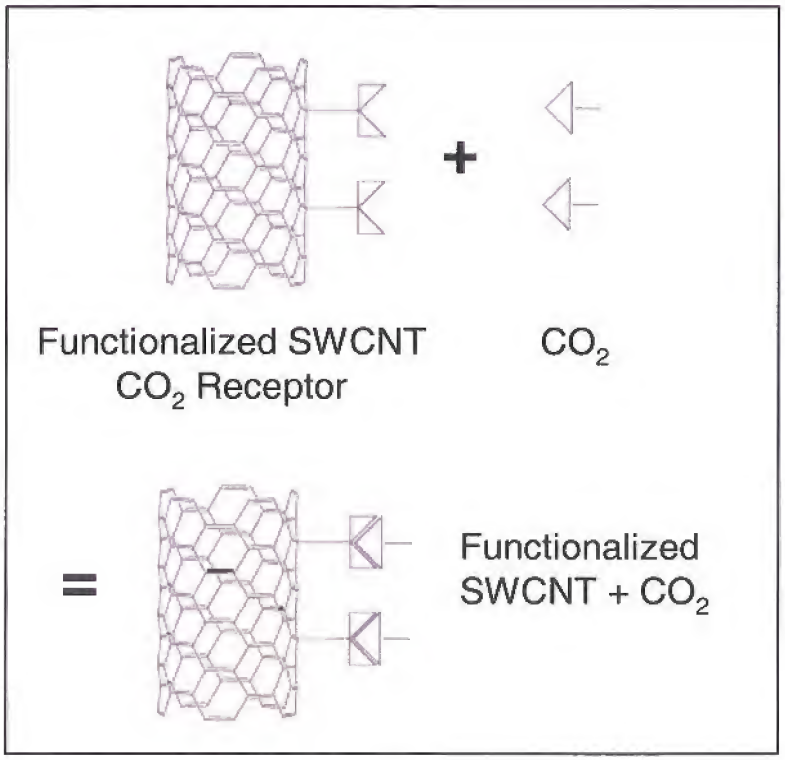
# Exploration Life Support: Regenerable $CO_2$ Removal

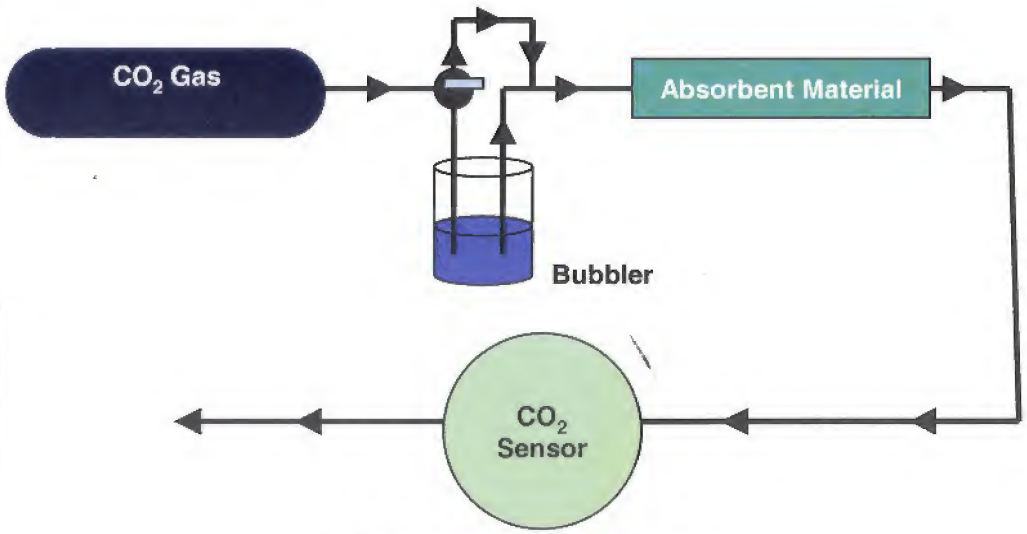
## NanoMaterial Solution:

- Use SWCNT functionalized with $CO_2/H_2O$ scavenging amines
- Amines require lower energy for regeneration than present molecular sieve
- Higher surface area reduces system size/ weight




**Nanotube functionalization chemistry**
(Chattopadhyay et al, 2005)

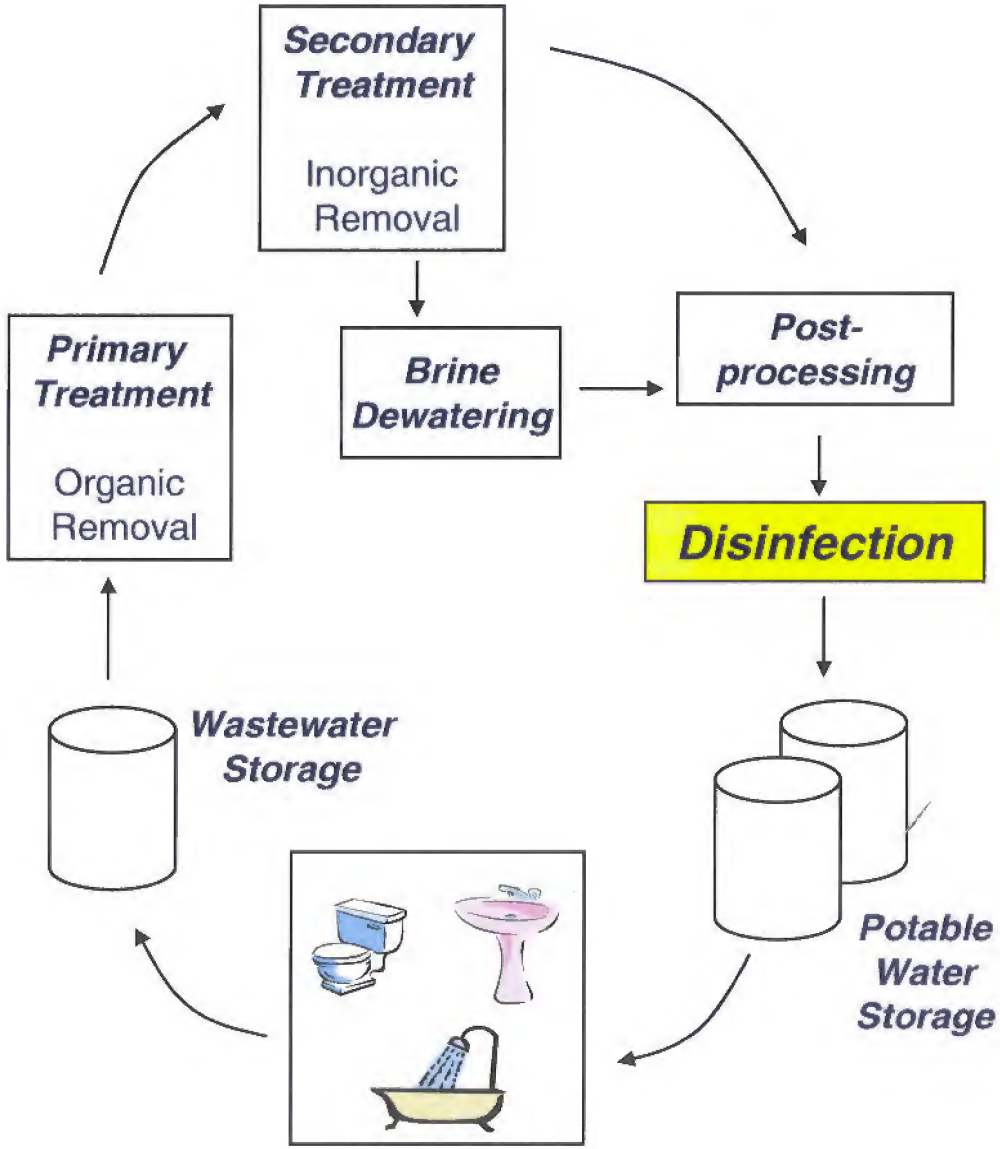



**$CO_2$ capacity testing**

# Exploration Life Support: Water Recovery

- Transport and storage of wastewater from human interfaces
- Primary processing: organic and nitrogenous contaminant reduction
- Secondary processing: inorganic contaminant reduction
- Brine dewatering: water removal from highly concentrated brine
- Post-processing and disinfection: polishing to meet potability standards
- Storage and transport of potable water prior to consumption



# Advanced Life Support: Water Disinfection / Recovery

## CHALLENGE:

- NASA requires renewable chemical-free systems to purify water in space
- Current solution: Iodine – toxic to astronauts and non-regenerable

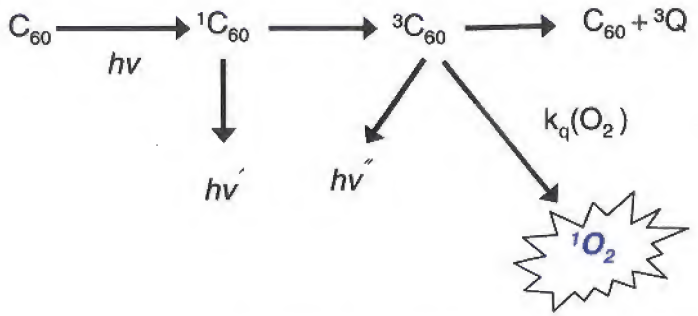
## SOLUTION:

- $C_{60}$ /fullerene enhances disinfection property of UV light
- Singlet oxygen production enhances the rate at which bacteria are killed
- Chemical-free system for closed loop water purification
- Commercial Potential - Portable water disinfection devices

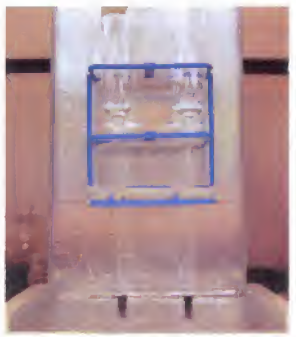
## COLLABORATION:

- NASA JSC Advanced Life Support (EC)
- Rice University: $C_{60}$ deposition

RICE




UV light energizes fullerenes. Upon relaxation, photons are emitted and the excited fullerenes interact with oxygen molecules in water to produce singlet oxygen.
*Singlet oxygen kills bacteria.*



**Water purifier cell**

**UV Light source**

# Power & Energy: Supercapacitors

## CHALLENGE:

- NASA requires reliable, robust power sources suitable for both EVA and vehicle applications
- NASA requires increased power & energy densities, increased cycle life, reduced mass

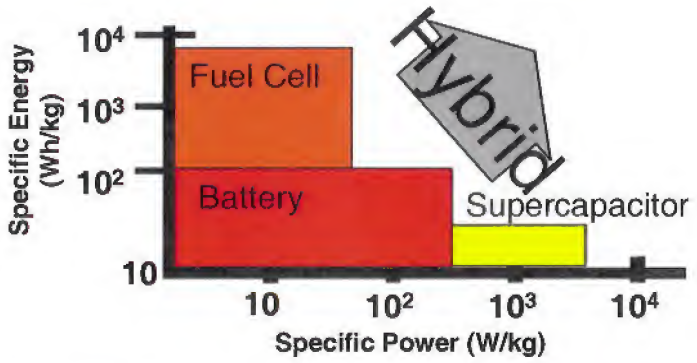
## SOLUTION:

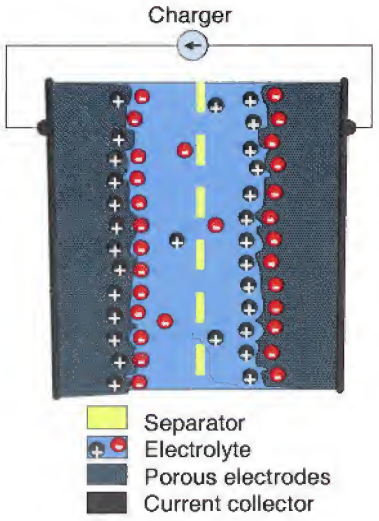
- Carbon nanotube surface area and nanoporosity superior to current materials for electrolyte ion support
- Carbon nanotube electrolyte supports: enhanced electrical and thermal conductivity
- Potential for enhanced performance and longer cycle life

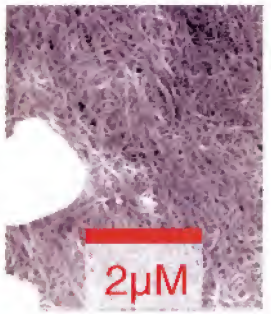
## COLLABORATION:

- NASA Glenn: Separator materials
- JSC (EP): Requirements
- Georgia Tech: Functionalized nanomaterials
- ReyTech Corp.: Improved fabrication & packaging

Power-Energy Tradeoff




Nanotube electrolyte support

Supercapacitor test cell

Georgia Tech Research Institute

# Power & Energy: Fuel Cells

## CHALLENGE:

- NASA requires reliable, robust power sources suitable for both EVA and vehicle applications
- NASA requires increased power & energy densities, increased cycle life, reduced mass

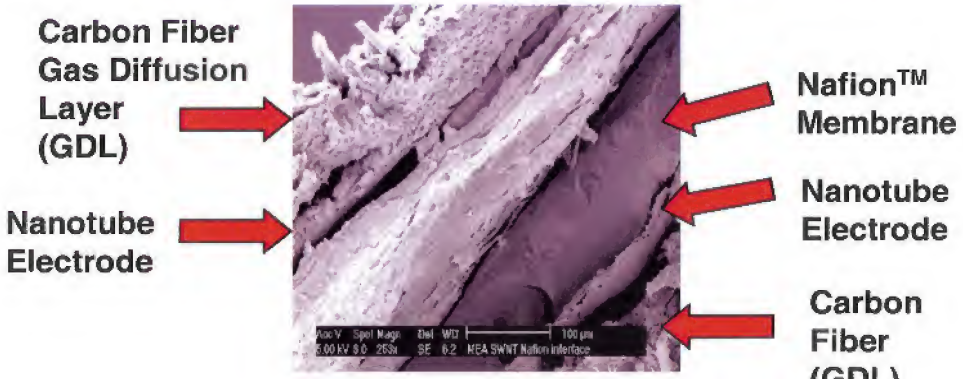
## SOLUTION:

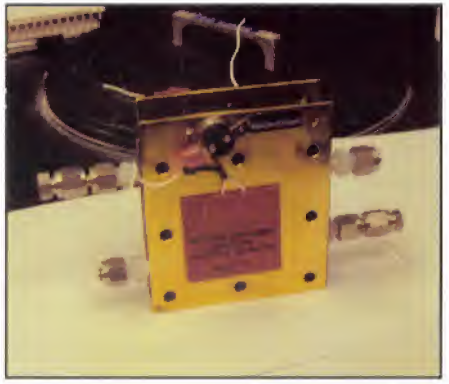
- Novel carbon nanotube high surface area, high thermal & high gas diffusivity catalyst support
- Reduced activation polarization – increased reliability
- Higher power density from more efficient utilization of platinum catalysts

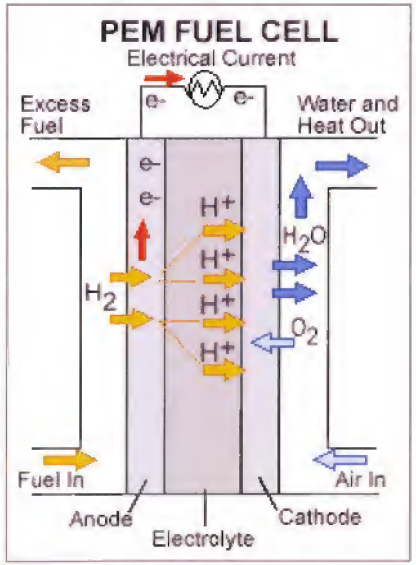
## COLLABORATION:

- NASA Glenn: High temperature membranes
- JSC (EP): Testing, requirements

### Prototype Membrane Electrode Assembly






**PEM Fuel Cell Schematic**
(Dept. of Energy)

# NanoMaterials for EMI Shielding

## CHALLENGE:

• Control of electromagnetic emission and susceptibility characteristics of electronic, electrical and electromechanical equipment and subsystems for space exploration

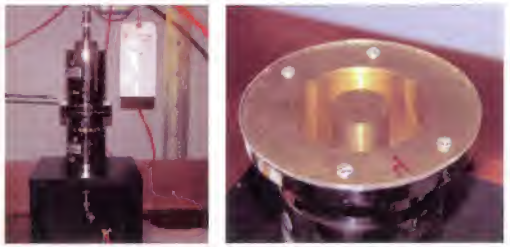
## SOLUTION:

• Single-wall carbon nanotubes (SWCNT) offer low material density and high electrical conductivity
• Can be integrated into polymer matrices as well as applied onto surfaces as thin **transparent** coatings
• Cheap & ease of fabrication for application to off-the-shelf products: Laptops, PDAs etc.

## COLLABORATION:

| | |
|---|---|
| •UTD: | Nanotube materials |
| •UTPA: | EMI testing & test development |
| •U of Florida: | Nanomaterials functionalization |
| •Rice: | Nanomaterials functionalization |
| •JSC (EV): | Testing, requirements |


**Translucent Appliqués: Potential coatings for LCD screens**



**EMI testing in collaboration with UTPA**

RICE

UTPA
The University of Texas-Pan American

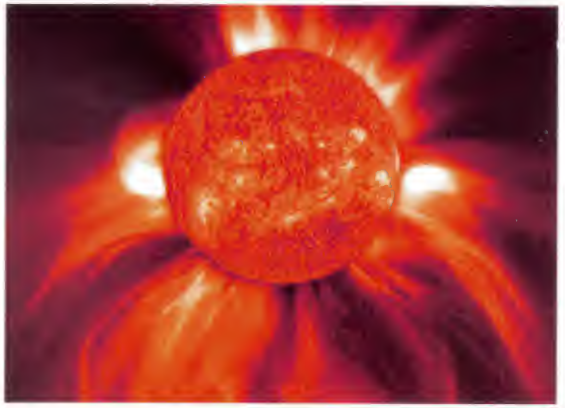
UTD

UNIVERSITY OF FLORIDA

# Active Radiation Dosimeter

## CHALLENGE:

- Acute radiation sickness poses a risk to astronaut health for interplanetary travel
- Currently no "real-time" personal radiation detecting sensor for extravehicular activity
- Current technologies lack desired sensitivity

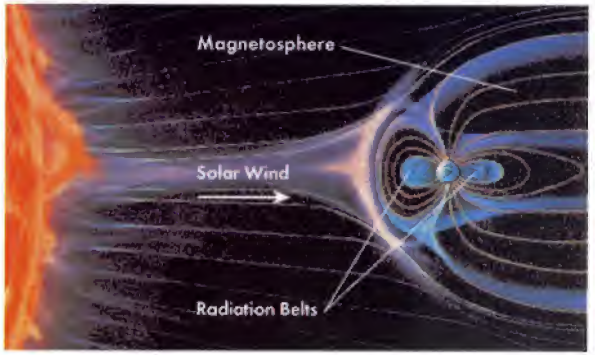


Solar Particle Event

## SOLUTION:

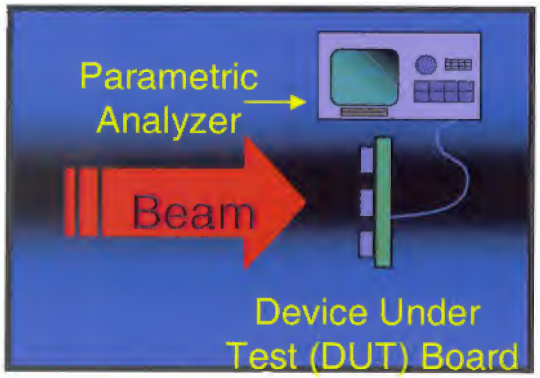
- Use radiation sensitive functionalized SWCNTs to measure radiation dose rates and total dose.
- High surface area nanomaterials can increase sensitivity

Earth's Protection




## COLLABORATION:

| | |
|---|---|
| • JSC (SF) | Dosimeter |
| • JSC (EB) | Sensors |
| • JSC (EC) | Advanced EVA |
| • NASA Ames | Gas sensors |
| • Rice Univ. | Nanotube functionalization |
| • PVAM | Radiation Testing |




Radiation Testing

# Advanced Thermal Protection System (TPS) Repair

## CHALLENGE:

- Improve and expedite curing and repair processes for current missions
- Long duration missions need more effective repair processes: On Orbit/En Route/On the surface

## SOLUTION:

- Use microwave energy to heat nanotubes in polymer and ceramic matrices for localized heating, curing & bonding
- Repair of RCC and tiles, CEV materials
- Potential commercial applications including composite curing

700 W
2.45 GHz


**~ 1:1 Energy transfer in nanotubes**

**Microwaves:Heat**

## COLLABORATION:

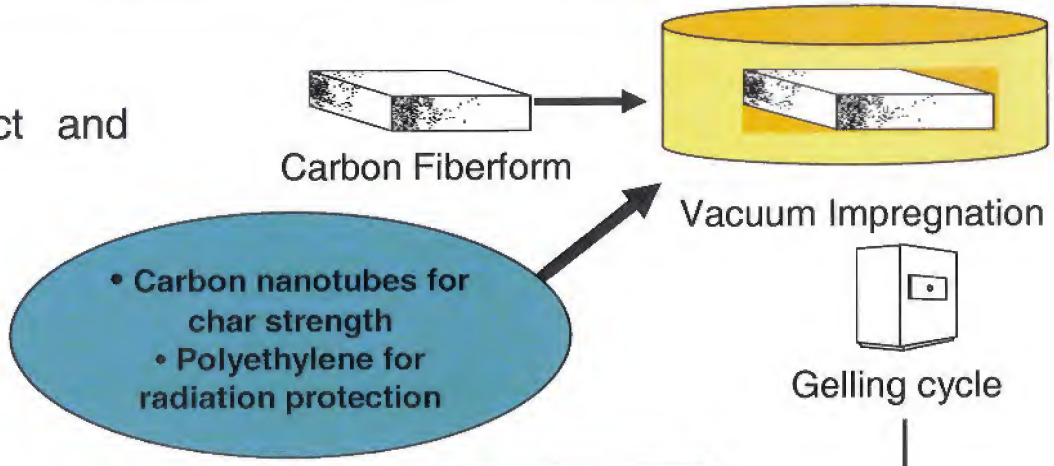
- Rice: Nanotube microwave research (Tour)
  Functionalized nanomaterials

RICE

# Thermal Radiation & Impact Protection (TRIPS)

## CHALLENGE:

- Thermal protection system with impact and radiation protection
- Lower weight = Greater performance
- Lower spacecraft complexity = Lower risk
- Lower risk = Greater safety




## SOLUTION:

- Use SWCNT impregnated into Phenolic Impregnated Carbon Ablator (PICA) Thermal Protection System (TPS) – additional strength
- Enhanced radiation protection via integration of polyethylene
- Nextel and/or Kevlar fabric incorporated for impact protection

## COLLABORATION:

- NASA Ames: TPS Lead
- JSC (ES3): Composites, Arc Jet Testing

PICA with phenolic resin impregnated

PICA - Fiberform before impregnation

# Nanotechnology: Astronaut Health Management

## Basic Biomedical Research

- The role that forces play on cell mechanisms (gravitational forces)
- Molecular machines (ATPase, Kinesin, Microtubules, Polymerase, etc.)
- In vivo monitoring of ultra-low concentration proteins and biomolecules

## Personal Biomedical Monitoring

- Identification of molecular indicators for onset of conditions
- High sensitivity assays
- Short prep-time assays, no prep-time assays and in vivo monitoring
- Multiple simultaneous assays

## Personal Countermeasures

- Timed drug release
- Targeted drug therapy
- Triggered drug release
- Indicators for drugs effectiveness

## Major Medical Operations

- Contrast agents to target specific sites for surgery
- Bio-mimetic or engineered compounds to help wound healing
- Miniaturized electron microscopes for biopsies

## Life Support

- High surface area materials for $CO_2$ removal
- Inorganic coatings that catalyze the revitalization of air and water
- Sensors to monitor harmful vapor/gases

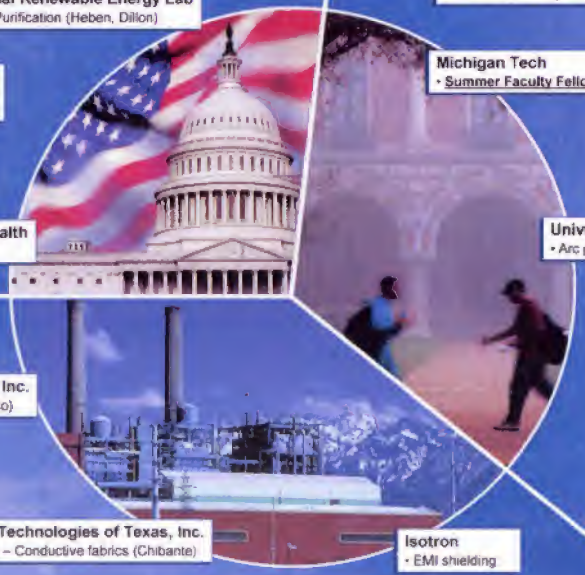
## Toxicology & Ethics

- Biodistribution of nanoparticles
- Toxicology of nanoparticles
- Ethical use of information from nanotech devices

## Systems Integration

- Develop 'common toolkit' for bio-nano chemistry and assembly processes

# JSC Nanomaterials Group Collaborations



## Government

**National Institute of Standards and Technology**
- Development of nanoscale measurement standards (Frieman)

**NASA Langley Research Center**
- Production / purification (JSC) for use in SWNT composites (Siochi, Park, Smith)

**Central Intelligence Agency**
- Nanotube characterization (Carr)

**Oak Ridge National Lab.**
- CNT production, purification and characterization (Geohegan)
- Thermal characterization (Wang)

**NASA Ames Research Center**
- Nanotubes (JSC) for sensors / modeling of HiPco (Meyyappan, Srivastava)

**National Renewable Energy Lab**
- CNT Purification (Heben, Dillon)

**NASA Glenn Research Center**
- Functionalization, purification, high temp mat'ls (Meador, Gray)

**Air Force Research Lab.**
- Composites, characterization, purification (Maruyama, Strong)

**NASA Marshall Space Flight Center**
- Nanotubes, MMCs (Gill, Hudson)

**Naval Research Lab.**
- Composites (Imam, Pehrsson)

**Los Alamos National Lab**
- Purification (O'Connell)

**National Institute for Occupational Safety and Health**
- Nanotube toxicology studies (Shvedova)

## Academia

**NASA-URETI: Texas A&M, Rice, UT Arlington, TSU, PrairieView A&M and UH**
- Nanotube characterization
- Radiation protection
- Mechanics / composites

**Rice University**
- Advanced Nanotechnology Mat'ls and Applications (Smalley, Tour, Barrera)
- Computational Mat'ls Sci (Yakobson)
- Nanoshells (Halas)

**University of Houston**
- GSRP, year 3 of 3 – Polymer chemistry, dispersion, composites (Mitchell, Krishnamoorti)

**Michigan Tech**
- Summer Faculty Fellow - Composites (Caneba)

**UC Riverside**
- Purification / characterization (Haddon)

**Georgia Tech**
- Nanotube composite films (Ready)

**University of Paris 13**
- Arc process (Farhat)

**University of Pennsylvania**
- CDDF - Thermal Mgmt. Mat'ls (Fischer)
- Composites (Luzzi, Winey)

## Industry

**SouthWest NanoTechnologies, Inc.**
- SBIR - Nanotube production (Resasco)

**Carbon Nanotechnologies, Inc.**
- Production, purification, applications (Smith)

**Zyvex**
- SBIR – Dispersion (Randall)

**NanoTechnologies of Texas, Inc.**
- SBIR – Conductive fabrics (Chibante)

**Isotron**
- EMI shielding

**Hamilton-Sundstrand**
- $CO_2$ Scrubber (Papale)

**Resolution Performance Products**
- Epoxy / nanotube composites (Stark)

**Inorganic Specialists**
- SBIR - Electrochemical capacitors (Firsich)

**Nantero, Inc.**
- NanoRAM development (Siegel)

**ReyTech**
- SBIR – Ultracapacitors (Reynolds)

**Ionwerks**
- Mass spectrometry (Schulz)

**COI Ceramics**
- RTF – Ceramic / nanotube composites (Riedell)

**Nanospectra**
- Thermal control coatings (Watkins)

**Eikos**
- EMI Shielding (Glatkowski)

**Materials and Electrochemical Research**
- SBIR - Nanotube production (Loutfy)

**Honda**
- Magnetic characterization (Harutyunyan)

**GB Tech**
- Fuel cells / $CO_2$ scrubber (Huffman)

**University of Florida**
- Isolated SWNTs (Rinzler)

**University of Tennessee, Knoxville**
- Nanoindentation (Penumadu)

**Northwestern**
- Nanomechanics (Ruoff)

**University of Oklahoma**
- Thermal stability of nanotubes (Resasco)

**LeTourneau University**
- Summer Faculty Fellow
  Nanotube growth process (DeBoer)

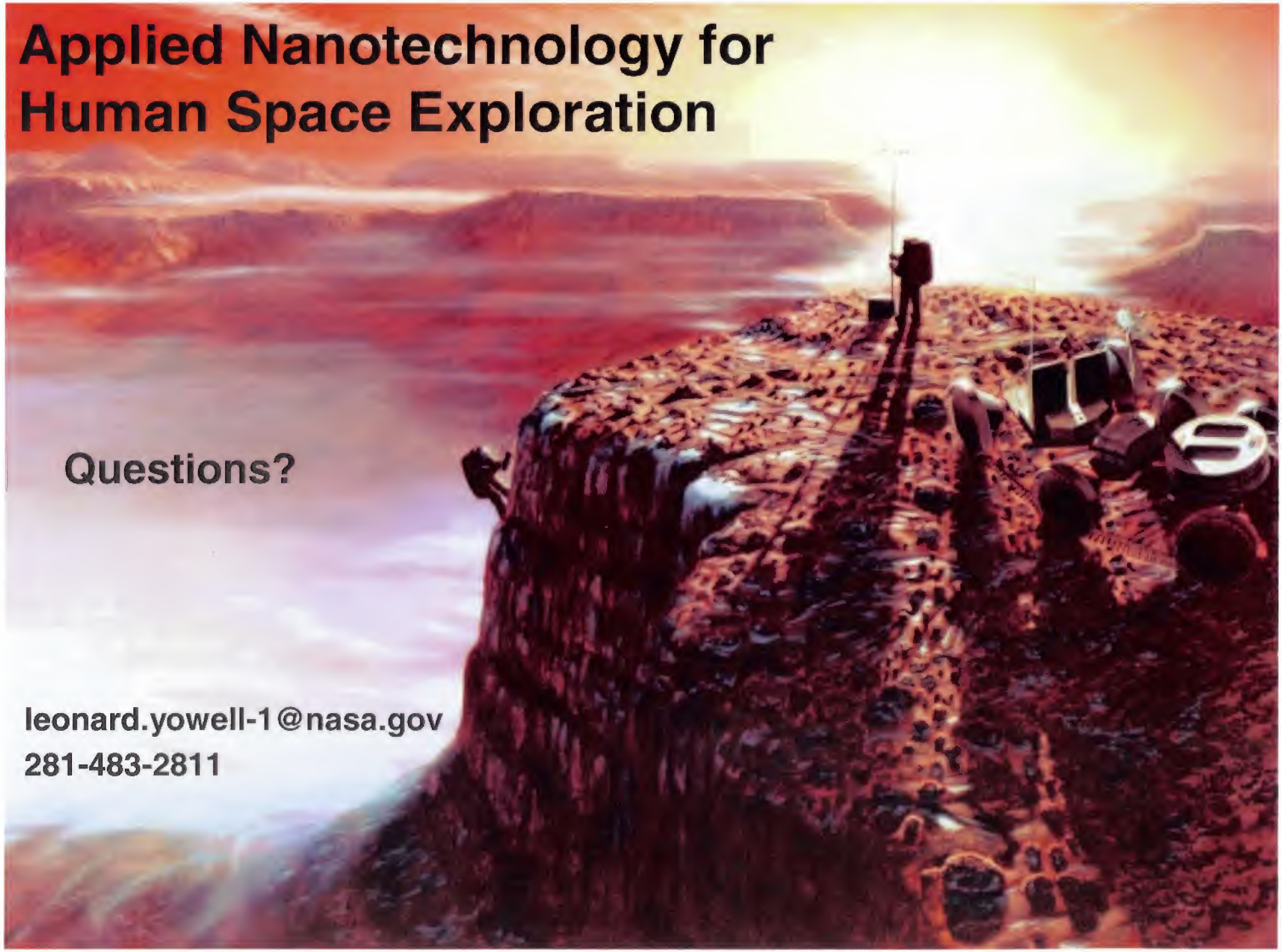
**University of California - Davis**
- Nanocrystalline Ceramics (Mukherjee)

**Penn State**
- Purification / characterization (Eklund)

**University of Texas - Tyler**
- Summer Faculty Fellow – CFD of Laser process (Greendyke)

**Wake Forest**
- Characterization of nanotubes (Carroll)

# Applied Nanotechnology for Human Space Exploration



Questions?

leonard.yowell-1@nasa.gov
281-483-2811